

THE EFFECTS OF HARVESTING ON LONG-TERM SOIL PRODUCTIVITY IN SOUTHERN INDIANA OAK-HICKORY FORESTS

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Abstract—Timber harvesting has the potential to alter long-term soil productivity in a variety of forest ecosystems. We monitored the effects of harvesting on N cycling processes in upland oak-hickory forests of southern Indiana, using a chronosequence of stands ranging in age from 1 year to 100 years after harvest. N cycling pools and processes were monitored from 1995-1999. Results suggest that reestablishment of fine root biomass occurs long before recovery of leaf area. The forest floor increases in relative importance for nutrient cycling with stand age. Litter decomposition is similar among stand ages. Estimates of actual evapotranspiration were significantly correlated with N cycling at most stages of forest development. There is a balance of litter N inputs, N mineralization, and N uptake at all stages of stand regeneration except at maturity. At this stage, litter N inputs were generally lower than N mineralization and N uptake.

INTRODUCTION

Data from various studies on forest N cycling at different stages of stand development can be used to reach general conclusions about ecosystem integrity, stand regeneration and nutrition, and recovery of N cycling pools and processes. Organization of the data into a conceptual model of N balances is one approach that can be used to make these assessments.

Two of the keys to the development of N cycling models are 1) the identification of the major ecosystem N pools and the transfer rates among these pools, and 2) an understanding of the degree to which N cycling is governed by internal pools and processes and external environmental factors.

For temperate hardwood forests, soil inorganic N is the major pool from which N is taken up for plant growth and metabolism (Nadelhoffer and others 1984). Much of the N is derived from the decomposition of vegetative N demand and uptake (Gholz and others 1985, Hendrickson 1988, Crow and others 1991). This may lead to a net loss of ecosystem N. As regeneration proceeds, this may lead to N limitations and reduced long-term site productivity. Only by monitoring N cycling at different stages of forest development, though, can these inferences be confirmed.

MATERIALS AND METHODS

We monitored various aspects of N cycling across a 100-year chronosequence of upland oak-hickory forests in southern Indiana, USA. Vegetation and site characteristics are listed in table 1. All of the regenerating stands were

clear-cut harvested and represent different stages of forest development from recently-harvested through maturity. Litter production, litter decomposition, N mineralization and nitrification, N uptake, and soil temperature, moisture, and actual evapotranspiration were monitored from 1995-1999, although not all measurements were made in all years.

The data were compiled into a conceptual model of nutrient cycling, and simple correlation analysis was used to discover the relative strength of internal and external controls over N cycling at different stages of forest development. The basic design of the N balance model is similar to the one presented by Aber and others (1991) for the nutrient cycling model VEGIE (figure 1).

In the conceptual models below, boxes represent ecosystem pools of N. Arrows between boxes represent transfer rates of N. Circles represent factors that influence N cycling pools and processes. Pool sizes and transfer rates are given in kg N ha/yr per yr. Values inside circles represent the strength of the correlation (R-value). Because annual rates of N cycling were of interest, the year 1998, in which data was collected from April-December, was used to make assessments of net N mineralization, net nitrification, N uptake, and soil microbial biomass N (SMBN). During 1997 and 1999, N cycling measurements were made during fewer months of the year, so these data were not considered to be representative of annual N cycling rates. Relationships between AET and SMBN, AET and net N mineralization, and between net N mineralization, nitrification, and N uptake, however, were all based on three-year cumulative data. Data for fine root mortality and litter pool size come from Idol and others (2000). Data for litterfall

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and forest floor mass come from Idol and others (1998). Data for woody debris come from Idol and others (1999). A question mark (?) represents missing data in the model.

RESULTS AND DISCUSSION

80-100 Year-Old Stand

Figure 2 illustrates the N balance model for the mature, 80-100 year-old stand. This forest should be near steady-state N cycling as discussed by Attiwill and Adams (1993). Specifically, there should be a balance of litter decomposition, net N mineralization, and subsequent litter N return. According to the N balance model, annual net N mineralization (150 kg N/ha) and N uptake (142 kg N/ha) are quite similar, but N returns from annual fine root mortality plus aboveground litterfall are somewhat lower (102 kg N/ha). N returns from woody debris are unknown but are likely to be small relative to fine root and litterfall returns, as this stand has not yet reached an old-growth stage where there is significant mortality of overstory stems (Jenkins and Parker 1998, Spetich and others 1999). Annual litterfall may have been underestimated by 10-20 percent because only autumnal litterfall was collected (Idol and others 1998). Even so, total litter returns are still 30-35 kg N/ha less than total N uptake. Assuming a woody production rate of approximately 5 Mg/ha with a N concentration of 0.2-0.4 percent (Perry 1994), perennial biomass N accumulation probably does not exceed 10-20 kg N/ha. Fruiting structures such as acorns (oaks), nuts (beech and hickories), and samaras (maples) may account for some of the remaining N.

1-8 Year-Old Stands

Figure 3 illustrates the N balance model for forest stands aged 1-8 years after harvest. Although woody debris (WD) from logging slash adds a significant quantity of organic matter to the litter pool (Idol and others 1999), the total N content is comparable to that found in the mature forest stand (156 kg N/ha). Because higher soil temperatures in the regenerating stands may lead to faster decomposition rates, the decay of this poor quality WD litter likely leads to an increase in soil microbial biomass N (SMBN) (283 kg N/ha). This increase in SMBN may depress annual net N mineralization rates in the first year or two after harvest (110 kg N/ha). By 6-8 years after harvest, however, SMBN is similar to pre-harvest levels (150 kg N/ha). At 6-8 years, net N mineralization and N uptake from the A (80 kg N/ha) but not the B (~50 kg N/ha) horizon is also similar to preharvest levels. Fine root mortality (55 kg N/ha) and the fine root litter pool (18 kg N/ha) are similar to preharvest levels.

Net N mineralization, N uptake, and litter production balance quite well in the model of recently harvested stands (figure 3). Although no data on fine root mortality or litterfall were collected for the stand aged 1-3 years, estimates at 4-5 years suggest these litter sources probably add 110-130 kg N/ha annually. Annual net N mineralization and N uptake also range from 110-130 kg N/ha. This suggests that little incremental biomass is being accumulated during the early stages of forest regrowth. This agrees with earlier studies that showed recently-harvested stands in this region are dominated by herbaceous annuals and perennials (Matson and Vitousek 1981, Idol and others 2000), plants that retain little residual biomass from year to year.

Table 1—Vegetation and Soil Characteristics for a Chronosequence of Upland Oak-Hickory Forests in Southern Indiana

Stand Age	Major Canopy Species	Major Understory Species	Dominant Soil Series	Soil Horiz.	Bulk Density (g cm ⁻³)	pH	Total C	Total N
0-8	<i>Liriodendron tulipifera</i> <i>Quercus alba</i>	<i>Smilax</i> spp. <i>Rubus</i> spp	Gilpin	A	1.20	5.41	35.1	4.63
				B	1.32	4.88	6.10	1.26
10-15	<i>Prunus serotina</i> <i>Quercus Rubra</i>	<i>Asimina triloba</i> <i>Sassafras albidum</i>	Gilpin	A	1.05	5.50	31.2	4.43
				B	1.35	4.81	5.84	1.01
30-35	<i>Acer saccharum</i> <i>Prunus Serotina</i>	<i>Acer saccharum</i> <i>Asimina triloba</i>	Gilpin/ Wellston	A	0.95	4.59	31.3	4.68
				B	1.10	4.71	5.42	1.14
80-100	<i>Quercus alba</i>	<i>Acer saccharum</i>	Wellston	A	1.02	4.59	27.4	4.12
				B	1.20	4.49	6.75	1.41

Sampled depths are 0-8 cm for the A and 8-30 cm for the B horizons.

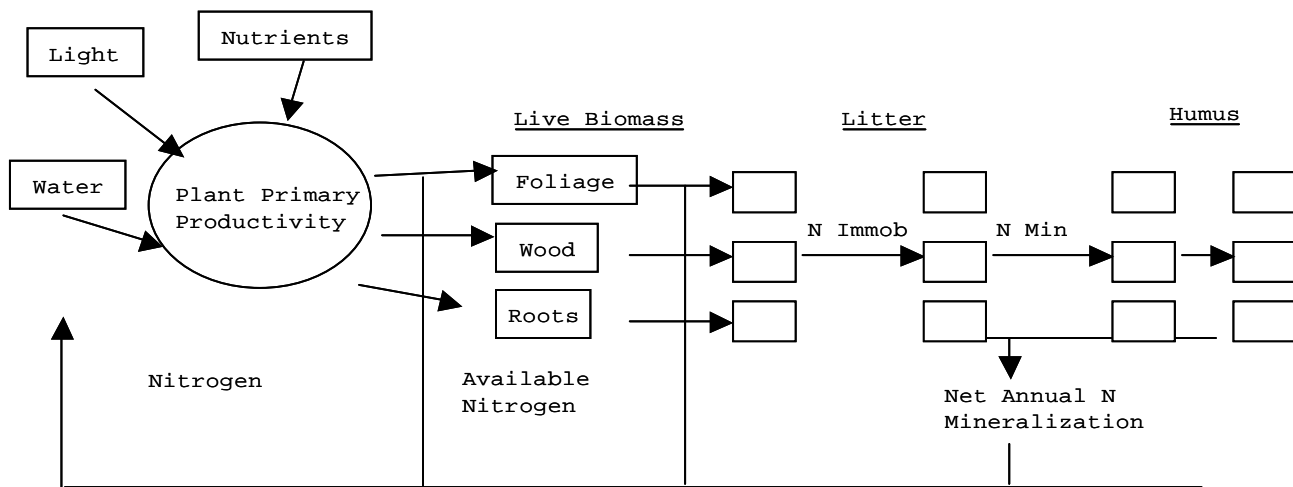


Figure 1—"VEGIE," a Generalized N Cycling Model (from Aber and others 1991). Values for boxes and arrows in kg N/ha-yr⁻¹. Values in circles represent strength of correlations (Pearson's correlation coefficient, R).

10-15 Year-Old Stand

Figure 4 illustrates N cycling patterns at stand age 10-15 years. Annual litterfall N returns are lower than at 1-8 years (27 kg N/ha), but fine root turnover is higher (69 kg N/ha). Forest floor mass and the fine root litter pool are higher (69 and 26 N/ha, respectively), but the lack of large WD inputs plus a possible slowing of litter decomposition may contribute to lower SMBN in the A horizon (57 kg N/ha). The available N pool is somewhat lower in the A horizon (6.8 kg N/ha) but slightly higher in the B horizon (12 kg N/ha).

Net N mineralization in the A and B horizons (41 and 65 kg N/ha, respectively) is very similar to N uptake (44 and 67 kg

N/ha, respectively). The total N uptake rate (111 kg N/ha) is slightly higher than the total litter production rate (96 kg N/ha), however, indicating some perennial biomass N accumulation. This is to be expected at this stage of forest development, as there is intense competition among tree saplings to reach the canopy before full canopy closure. Assuming a woody tissue N concentration of 0.2-0.4 percent, this balance of N uptake translates into a perennial biomass production rate of 12.5-25 Mg ha/yr.

30-35 Year-Old Stand

Figure 5 illustrates N cycling patterns at 30-35 years post-harvest. Annual litterfall N returns are higher at this stage

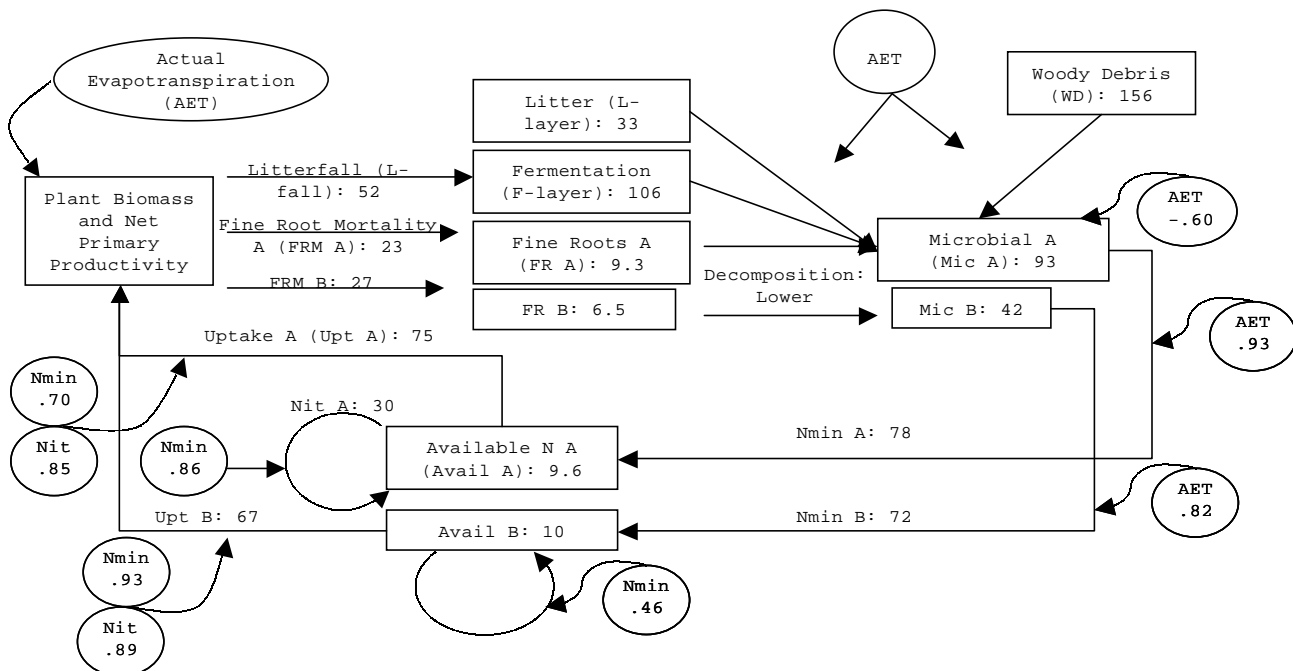


Figure 2—N Balance Model in an 80-100 Year Old Southern Indiana Upland Hardwood Forest. Values for boxes and arrows in kg N/ha/yr. Values in circles represent strength of correlations (Pearson's correlation coefficient, R).

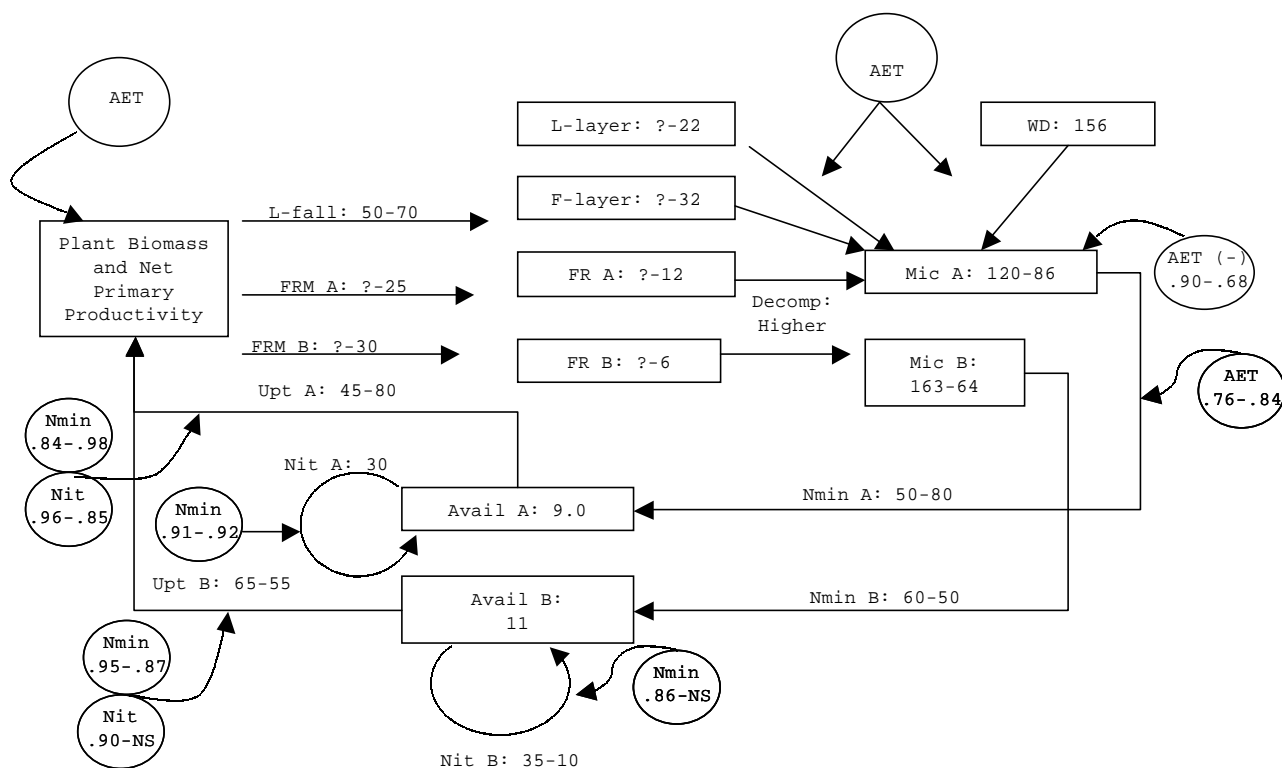


Figure 3—N Balance Model in Southern Indiana Upland Hardwood Forest Stands 1-8 Years Post-Harvest. Values for boxes and arrows in kg N/ha/yr. Values in circles represent strength of correlations (Pearson's correlation coefficient, R).

(38 kg N/ha) than at 10-15 years (27 kg N/ha), reflecting increased leaf area with increased stand age. Fine root mortality is similar in the A horizon (30 kg N/ha) but lower in the B horizon (32 kg N/ha). Forest floor mass is higher (98 kg N/ha), but the dead fine root pool is slightly lower (18 kg N/ha). Decomposition is assumed to be lower at this stage of forest development, but the SMBN pool is somewhat

higher (141 kg N/ha) than at 10-15 years of age (112 kg N/ha), perhaps due to declining aboveground litter quality. The available N pool is somewhat higher in the A horizon (7.6 kg N/ha) but lower in the B horizon (9.0 kg N/ha).

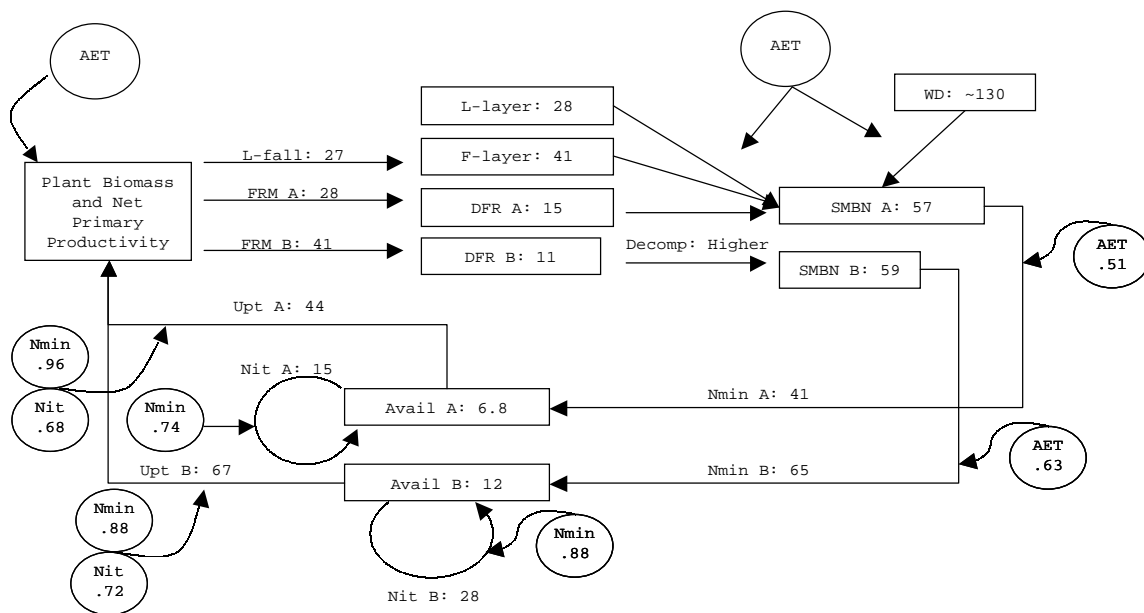


Figure 4—N Balance Model in a 10-14 Year-Old Southern Indiana Upland Hardwood Forest. Values for boxes and arrows in kg N/ha/yr. Values in circles represent strength of correlations (Pearson's correlation coefficient, R).

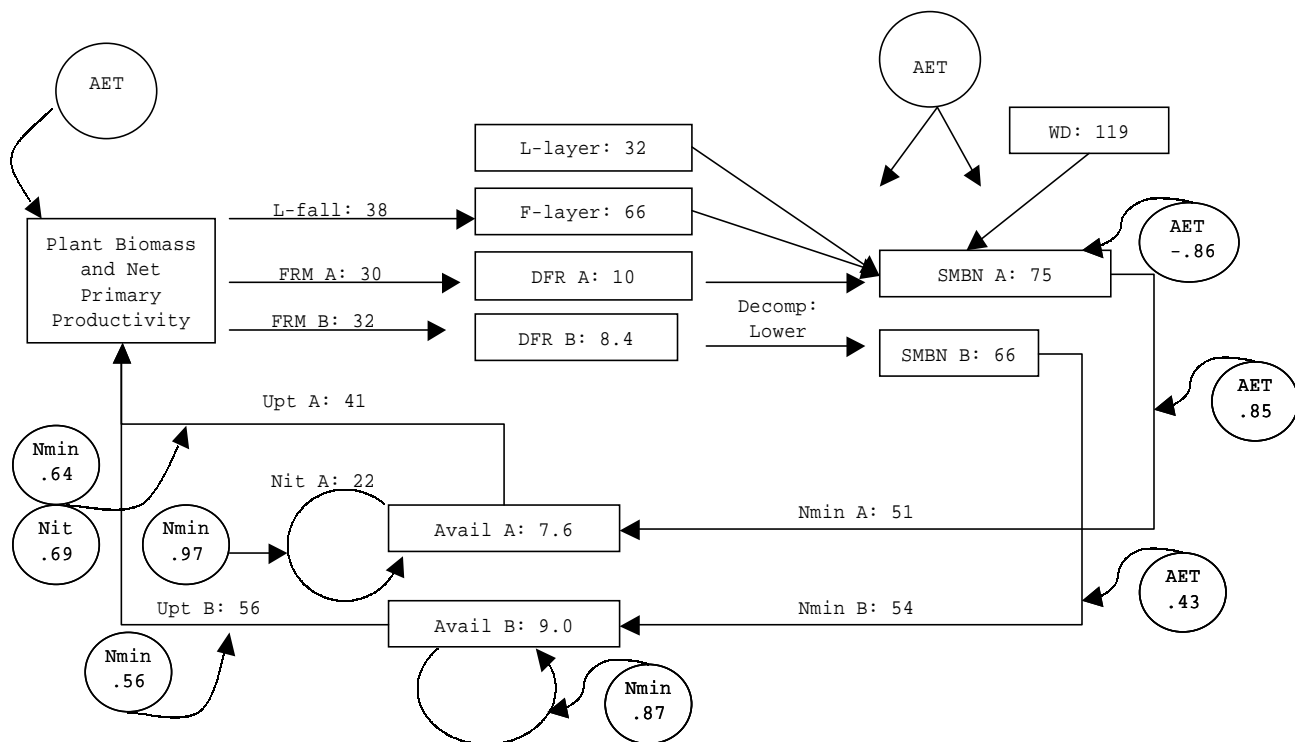


Figure 5—N Balance Model in a 29-33 Year-Old Southern Indiana Upland Hardwood Forest. Values for boxes and arrows in kg N/ha/yr. Values in circles represent strength of correlations (Pearson's correlation coefficient, R).

In the B horizon, net N mineralization (54 kg N/ha) is similar to N uptake (56 kg N/ha), but in the A horizon, net N mineralization (51 kg N/ha) is somewhat greater than N uptake (41 kg N/ha). Total N uptake (97 kg N/ha) and net N mineralization (105 kg N/ha), however, were similar to total litter production (100 kg N/ha), indicating that perennial plant growth may be slowing in this stand, and N cycling is approaching steady-state. This is in contrast to the higher net N mineralization and uptake (~145 kg N/ha) vs. total litter production (102 kg N/ha) rates in the mature forest stand (figure 2).

Controls Over N Cycling Rates

In stands of all ages, actual evapotranspiration (AET) correlates significantly and in some cases strongly with net N mineralization and N uptake. There is no consistent pattern with stand age, but in general relationships were stronger between AET and N cycling in the A horizon than in the B horizon. Relationships were generally strongest with net N mineralization and weakest with soil microbial biomass N and net nitrification.

The strongest relationships, however, were among the N cycling processes themselves. In general, net nitrification and N uptake were more strongly correlated with net N mineralization than with AET. In stands that are N-limited, N supply rates likely exert the strongest control over nitrification and N uptake, with environmental conditions (e.g., soil moisture and temperature) influencing the rate at which

available N is nitrified or immobilized by plants or soil microorganisms.

CONCLUSIONS

The conceptual models presented in this study were derived from investigations of N cycling pools and processes at different stages of forest development. In general, there was a good balance of N mineralization, N uptake, and litter N returns in the regenerating forest stands; however, in the mature stand, there seemed to be more N taken up than returned via fine roots and autumnal litterfall. N mineralization and uptake were higher in the mature stand (140-150 kg ha/yr) than in the regenerating stands (80-100 kg ha/yr). Although actual evapotranspiration (AET) correlated significantly with N cycling processes at all stages of forest development, nitrification and N uptake correlated more strongly with N mineralization than with AET. Thus, although N cycling processes are well-balanced at different stages of forest development, harvesting may lead to declines in overall N cycling rates for at least the first 30-35 years.

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